DEVELOPMENT AND IMPROVEMENT OF Q3s – A Three Year Old Child Side Impact Dummy

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Paper Number 09-0358

ABSTRACT

The research of child restraint systems tested under side impact test conditions has been conducted extensively in the past few years. In May 2008 US Government and Industry meeting, US National Highway Traffic Safety Administration (NHTSA) presented a summary of the 3 year old child side impact dummy evaluation result with some desired improvements, including the neck biofidelity and thorax rib cage durability. With further evaluation later at Ford, Transport Canada and NHTSA Vehicle Research and Test Center (VRTC), it was observed the hip ball popped out from the cup retainer during some of the tests. The overall biofidelity of this dummy was summarized by Carlson et al, and also updated biofidelity summary was presented by Rhule [3] in 2008 Government Industry meeting. This paper summarizes the improvements that address these identified issues in the past year.

INTRODUCTION

NHTSA Traffic Safety Facts 2007[4] data shows that there were 61 million children age 14 and younger in the United States, which is about 20% of the total US population in 2007. Motor vehicle crashes are the leading cause of death for ages 3 to 6. There were total 41,059 traffic fatalities in the United States in 2007. The 14- and younger age group accounted for 4 percent (1670) of these traffic fatalities. Research has shown that lap/shoulder seat belts, when used, reduce the risk of fatal injury by 45 percent and risk of moderate-to-critical injury by 50 percent. Research on effectiveness of child safety seats has found that they reduce fatal injury by 54 percent (1 to 4 years old) for toddlers in passenger cars. Among children under age 5, an estimated 382 lives were saved in 2007 by child restraint safety seats. It is obvious that child restraint systems play a significant role in saving children's lives. However, the NHTSA data shows 165 fatalities with the use of the child seat restraint systems for age group of 1-4 years old. The 165 fatalities account for nearly 43 percent of the total fatalities. These numbers imply that improvements to child restraint systems to better protect children are needed. The child dummy has served as a good tool to assess the protection of children. A biofidelic child dummy is essential in developing safer child restraint system.

As part of the efforts to develop a safer child restraint system, the Q dummy series was developed in Europe during 1995-2004. The dummy was developed to have more human-like anthropometry and performance as the next generation of the P child dummies specified in UNECE Regulation 44. The dummy was designed to perform in both frontal and lateral test conditions. With more field accident data and biofidelity data under side impact test condition, the Q3s was introduced focusing on improving biofidelity for side impact test.

The overall bofidelity evaluation result of the Q3s dummy was published by Carlson et al in 2007[1]. The biofidelity corridor was based on the work published in 2002 by Irwin et al [2]. Also additional neck torsion biofidelity requirement was proposed by Mertz (informal communication between Dr. H. Mertz and NHTSA Vehicle Research and Test Center). These criteria serve as the basis of the dummy biofidelity evaluation.

In the 2008 presentation from Rhule [3], the Q3s dummy showed superior biofidelity in shoulder, thorax and pelvis area compared to the Hybrid III 3 year old child side impact dummy, while it also showed the neck flexion and torsion biofidelity responses required further improvement. In addition, the thorax rib cage durability became a concern from testing. One rib cage cracked after approximately 90 tests (30 sled tests and 60 pendulum tests) at 25 mm chest deflection magnitude. In spring 2008, Occupant Safety Research Consortium (OSRP) of United States Council for Automotive Research (USCAR) found the hip joint ball came out in a test. This issue was also observed later in VRTC's sled test. This paper presents a new neck design for improved biofidelity performance and also summarizes the solutions to address the durability concerns of the thorax rib cage and hip joints.

NECK DESIGN

A new neck was designed to meet the flexion, extension, lateral bending and torsion biofidelity requirements. Since each test has its own performance specification, it requires a complex structure to meet these requirements simultaneously. The neck design consists of four aluminum vertebra discs and rubber segments between the aluminum discs. The rubber segments have an oval-like shape with circumferential V-shaped groves. The V shape opening angle varies around the neck in different locations (frontal, lateral and rear) in order to govern the performance of the neck. Cuts were introduced into the front of the neck to soften it, and comply with the extension performance requirement. The molded neck is shown in Figure 1. Different rubbers were experimented with to optimize the neck performance. The test data is summarized later in this paper.

Figure 1, molded neck

Figure 2, Neck assembly with cable

A torsion cable was designed into the neck assembly to govern the torsion performance. The cable has metal sheaths crimped to both ends. At one end, the metal sheath has a key to engage with a ring underneath to control the torsion performance of the neck. During the development of the previous torsion cable, it was found that the asymmetrical torsion cable caused asymmetrical performance, which requires offset of the key position to compensate and induce earlier rotation in order to gain symmetrical neck performance. It was found a symmetrical torsion cable was desired and identified in the design to eliminate the offset of the key feature. The cable and the rings are shown in Figure 2.

NECK TESTING SETUP

The neck biofidelity test was conducted on the pendulum specified in US Regulation 49CFR Part 572 with a special headform (same design as the Q3 frontal impact dummy). The neck was tested for flexion, extension, lateral bending with this headform as shown in Figure 3.

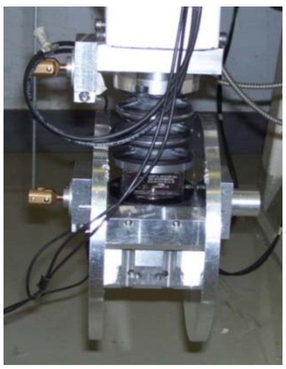

Figure 3, Headform for flexion, extension and lateral bending pendulum test

Figure 4, Headform for torsion pendulum test

The torsion was tested with a special headform designed by VRTC, shown in Figure 4. This headform has a neck load cell to measure the moment Mz of the neck and a rotary pot to measure its rotation about Z axis.

NECK TEST DATA

Neck flexion test was conducted at 5.5 m/s impact speed. Three necks with different rubber stiffness were fabricated for testing. The test results are shown in Figure 5.

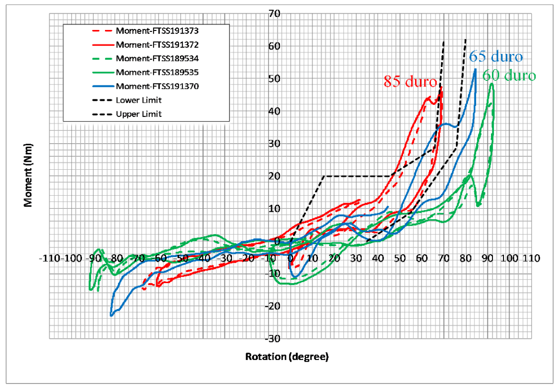

Figure 5, Flexion pendulum test, 5.5 m/s

From the test result, we can see that rubber with a stiffness range from 65 to 85 durometer shore A is close, but not well within the biofidelity specification.

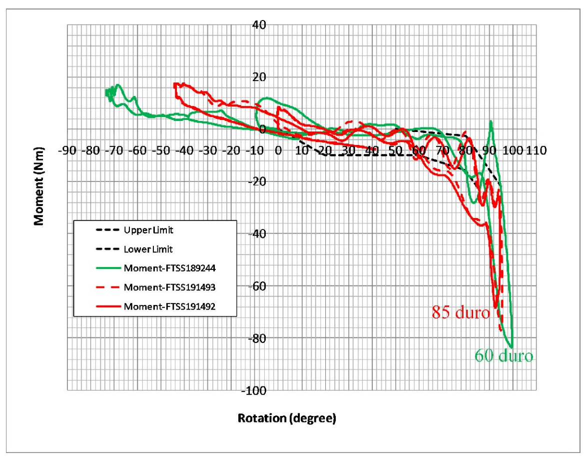

Figure 6, Neck extension pendulum test, 5.5 m/s

Neck extension test was conducted at 5.5 m/s impact velocity. The test result is shown in Figure 6.

The extension pendulum test shows close results for the neck with rubber stiffness at 65 and 85 durometer shore A. No significant performance difference was observed in the test results. During the neck extension test, the neck rotates up to a range of 90 to 100 degrees. At the maximum bending, the V groves are completely closed and bottomed out, causing the moment to increase quickly after it reaches 85 degrees.

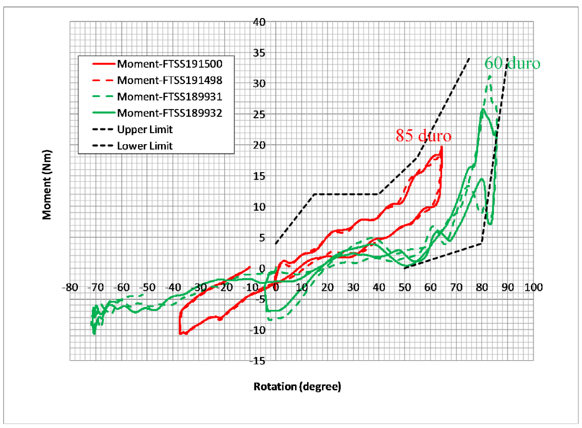

Figure 7, neck lateral bending test, 3.9 m/s

The lateral bending test was conducted at 3.9 m/s velocity. The test results are shown in Figure 7. We can see both necks with 60 and 85 durometer shore A meet the biofidelity corridor very well.

Neck torsion test was conducted with a special headform as described in the previous section. The test results are shown in Figure 8. From the test results, we can see the 85 durometer shore A rubber neck is too stiff to meet the test requirement, while 60 and 65 durometer shore A neck meet the biofidelity corridor very well. As mentioned in design section, the neck cable has an asymmetrical mechanical property, which requires offsetting the cable key to balance the rotation between the left hand and right hand rotations. At the submission of this paper, the symmetrical cable is in the fabrication process.

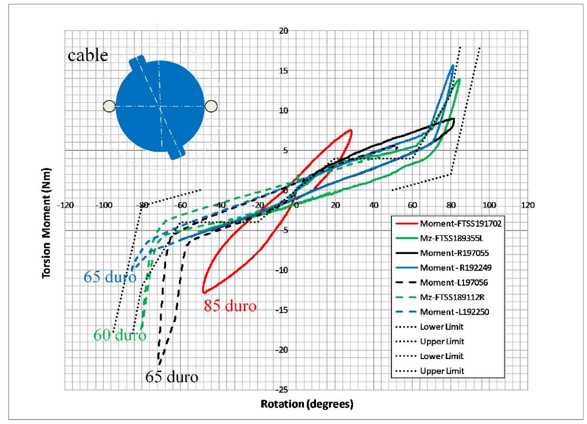

Figure 8, Neck torsion test, 3.6 m/s

From these tests, we concluded that the neck with 65 durometer rubber performs the best considering all four biofidelity requirements. However, we noticed the neck flexion performance, which is soft to meet the biofidelity requirements. After investigating the neck rubber geometry, we added some rubber material on the V grove at the front side of the dummy. This is to reduce the angle neck rotation before it bottoms out. It was also examined from CAD design that other performance would not be affected after this modification. A mockup neck was fabricated by gluing some additional rubber pieces to the corresponding area. The test results shows in Figure 9.

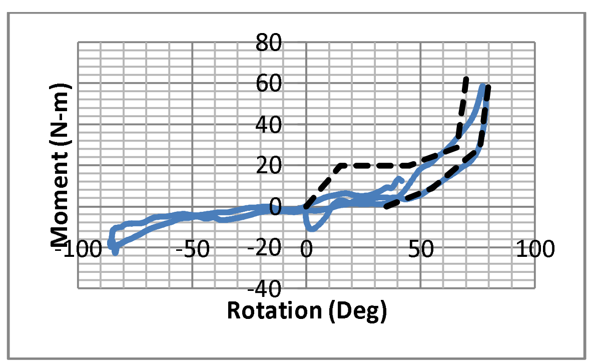

Figure 9, Neck flexion pendulum test, 5.5 m/s

The mold was updated to reflect the mockup design. At the time of submitting this paper final, the final version for neck is in the process of manufacturing.

THORAX RIB CAGE

Thorax rib cage is a critical component in the dummy design. It was observed that the rib cage was broken with a limited number of tests.

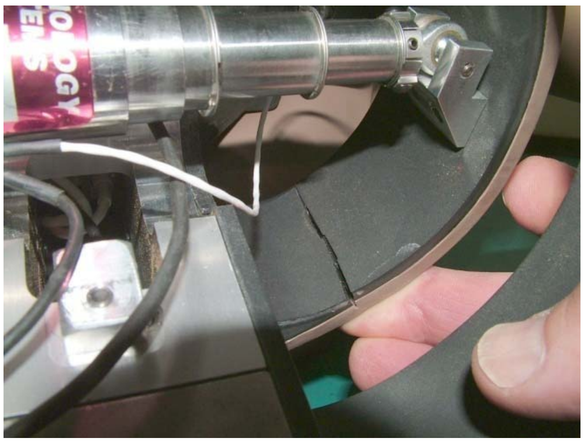

Figure 10, damage of the thorax rib cage

One rib cage was damaged after approximately 90 pendulum and sled tests combined, while another rib cage failed after 30 pendulum tests. The damage always happens toward the rear side of the rib contour as shown in Figure 10.

It was noticed some ribs have relative longer life than the others. From the analysis of the fractured surface, it has been noticed there were always defects, mainly air bubble like void on the fractured surface. These defects are typically buried inside and can't be observed visually in the quality inspection. The crack initiates from these defects and starts to propagate and become catastrophic. The rib cages that have very long life time, we believe have no such defect buried in the parts. Since it is difficult to inspect these invisible defects, quality control was a problem.

From the investigation of the damaged parts, it is clear that damage is a fatigue life issue. If we can make the design insensitive to the defects, it will elongate the life of the parts. To solve the problem, the following parameters were considered to increase the fatigue life cycles.

- Optimize the thickness of the rib to reduce the maximum stress level. If the maximum stress level was reduced, the fatigue life will increase accordingly.
- Introduce a Nitinol sheet metal insert. To maintain the same rib cage stiffness, therefore to maintain the same performance, the plastic material stiffness has to be reduced. When the plastic material stiffness is reduced, its elongation will be increased accordingly and fatigue life will increase accordingly. Also by introducing the Nitianol sheet metal insert, the plastic material thickness is as a consequence reduced. Under the same deflection level, the thinner plastic rib portion reduces the stress level as well from beam theory.

Finite element analysis was used to study the stress distribution of the fractured area, which was identified as the highest stress level in the whole rib cage. We noticed that the bending area was thickened in the early Q3 development, which was intended to address frontal failure. However, for lateral impacts, the damage shifted further forward to the thin area as it is now.

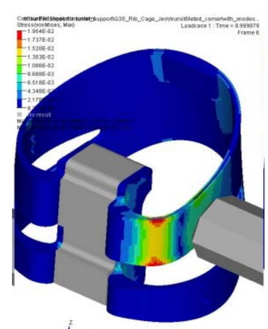

Figure 11a, FEA - the stress distribution of the rib cages (baseline – thickened contour)

We conducted analysis of the cage to compare the uniform thickness and the thickened design. It was found that rib cage with uniform thickness actually has less stress level than the thickened one that was intended to address the fracture.

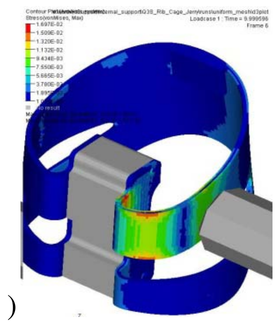

Figure 11b, FEA – stress distribution of the rib cage (uniform thickness)

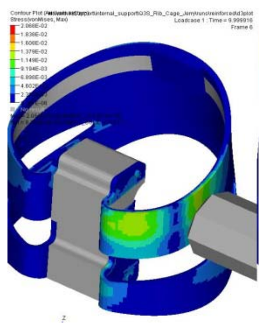

Figure 11c, FEA – stress distribution of the rib cage (uniform thickness with Nitinol sheet metal insert).

We also conducted an analysis of the rib cage with a Nitinol sheet metal insert to study the maximum stress level of the plastic material and also investigate if stiffness of the metal insert together with the plastic material is feasible to maintain the same dummy performance. The maximum stress is summarized in table 1.

From the analysis, we can see 25% stress reduction can be achieved with the Nitinol metal insert, and the proper stiffness of the rib cage can be achieved with proper combination of metal insert and plastic material stiffness.

Table 1, Max stress comparison of rib cage

Cases	Max Stress (MPa)	Reduction (%)
baseline	17.4	NA
uniform thickness	15.1	-13%
uniform thickness with insert	13.8	-25%

THORAX RIB CAGE TESTING

After the finite element analysis, prototype parts were fabricated accordingly for testing to validate the concept. The shape of the metal insert was optimized in design to address some manufacturing challenges. The final design of the rib cage with the insert is as shown in Figure 12.

Figure 12, Q3s rib cage design with metal insert

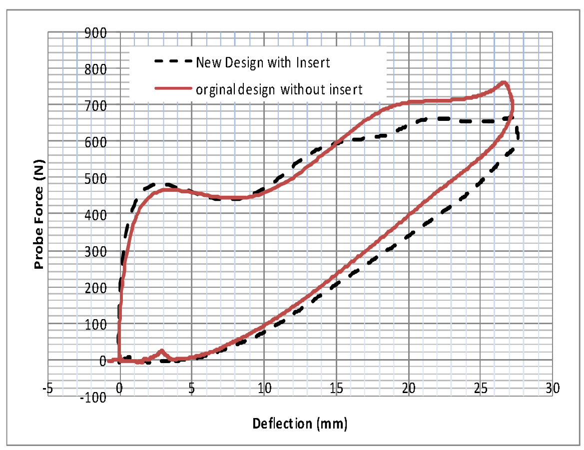

Figure 13, Pendulum impact test of the new rib cage and the old one.

The rib calibration with pendulum impact test was used to verify the rib performance. After eight iterations of refining the insert and plastic material, the performance is very similar to the existing rib cage. Further biofidelity tests will be conducted at VRTC in the near future.

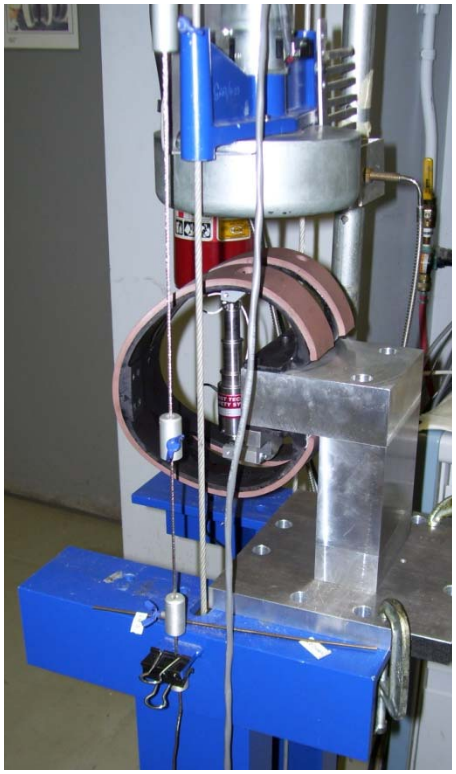

Figure 14, Rib durability drop tower test setup

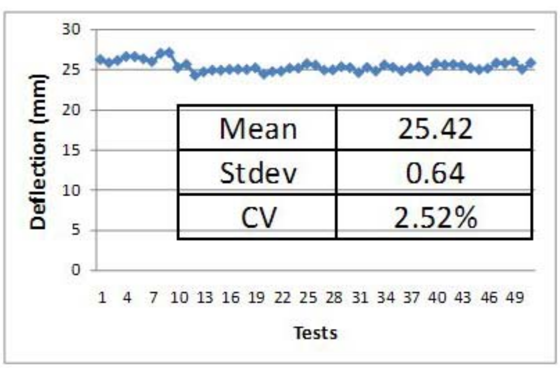

Figure 15, rib deflection under drop tower test (total 500 tests, data collected every 10 tests).

Drop tower testing was used to verify the durability of the ribs. The test setup is shown as Figure 14.

From the sled tests and pendulum tests performed previously, it was noticed the thorax was compressed to a level of 25 to 28 mm deflection. The drop tower reproduced this level of deflection for each impact. The rib cage was inspected carefully after each test.

Rib deflection data was collected every 10 tests. The deflection is plotted in Figure 15. From the data we can see the rib performance is very stable and there is no damage to the rib cage after 500 tests. The durability of the rib has improved significantly.

HIP JOINT DURABILITY

It was observed in some severe test condition, the hip ball popped out of the ball retainer, also referred as the cup.

Figure 16 Hip ball pop out from its cup

From the investigation, the cause of this problem was due to the plastic cup, not being strong enough to retain the hip joint in position. Under severe test condition, the hip cup will deform and allow the hip ball to slip out of the cup retainer. To address this problem, the deformation of the hip cup needs to be limited while the engagement between the ball and the cup needs to be improved.

To reengineer the joint, aluminum material was used to replace the plastic material for the cup, which increases the rigidity of the hip cup significantly. At the same time, the plastic hip ball and ball shaft was replaced with a hardened aluminum ball. The ball diameter was reduced from 30 mm to 25.4 mm, while the shaft diameter was reduced according to maintain the hip joint range of motion. This design change increases the engagement area between the ball and the cup and therefore strengthens the ball joint.

Figure 17, New hip joint design

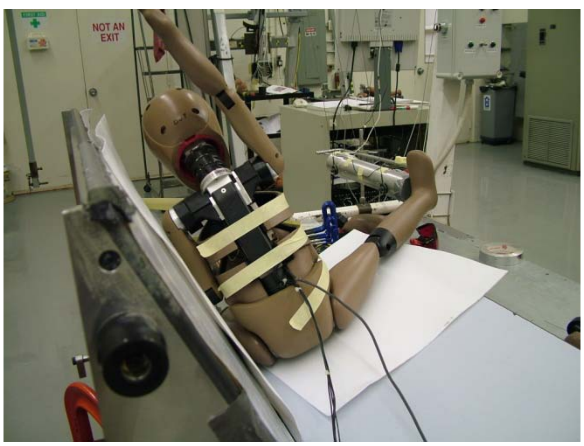

Figure 18, hip joint durability test (courtesy of VRTC)

A pendulum test was used to evaluate the new design at VRTC. The dummy was restrained in a test bench with one leg removed, and a pendulum was used to impact the other leg at the foot location from inboard. The test setup is shown in Figure 18. The plastic design hip joint ball popped out immediately, while the new design survived the test without any damage. The test was considered severe enough for the conditions that the dummy is used.

CONCLUSIONS

The few outstanding issues identified from 2008 Government Industry meeting and thereafter were addressed with new designs. The new neck design can meet the flexion, extension, lateral bending and torsion requirements. A robust rib cage design with identical geometry was validated and was shown to improve the durability significantly. A more durable hip joint design was evaluated as well. The design is very promising in a severe test condition and further evaluation will be conducted in the future. The Q3s dummy is ready as a robust tool for child restraint system development.

ACKNOWLEDGEMENT

The authors would like to thank the OSRP Q3s Task Group for the support and review of the development of the solutions, and also would like to express our appreciations to NHTSA/VRTC and Transport Canada for their contributions to the evaluation tests and instant feedback on the designs so that we can have these issues addressed in a timely manner. Also, special thanks go to Mr. Frank Laureto, who coordinated and fabricated all prototype parts.

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